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LASER DEVICE FOR DRILLING HOLES IN
COMPONENTS OF A FLUID INJECTION DEVICE

The present invention concerns a laser machining device for drilling holes in components of a fluid injection device, in particular for injecting fuel into a combustion engine. "Combustion engine" means any type of engine or reactor in which a fuel is supplied directly or indirectly to at least one combustion chamber via an injection
5 device. "Injection device component" means in particular injection nozzles, flow controllers or even filters.

Currently, various methods are known for drilling holes in the aforementioned components, particularly the use of certain laser devices. For example, the use of diode pumped solid state lasers (DPSSL), arranged with Q switch means for the
10 resonator, has been proposed. Such lasers generate a plurality of pulses whose very short period is generally much less than 1 μ s, for example 15 nanoseconds.

A laser device of the aforementioned type has already been made by various companies. The user of such a diode pumped crystal laser has numerous advantages relative to a flash lamp pumped crystal laser, for example an Nd:YAG laser. Indeed,
15 the use of such a flash lamp generates variations from one pulse to another, particularly a fluctuation in the intensity of the pulses supplied and a variation in the leading edge length of the pulses. Moreover, the resonator's stability is not very good, in particular because the active element is heated by the flash lamp which has a relatively broad transmission spectrum. The laser thus does not have optimum yield
20 since a part of the energy is not used for generating the laser beam. This also means that the active medium is subjected to thermal stresses which decrease the pulse transmission stability and quality. The major drawbacks of this are that the precision of the holes to be machined is limited and it is not possible to achieve good reproducibility from one hole to the next. Thus, the geometry of the holes made by
25 flash lamp pumped lasers has poor machining tolerances and does not allow the flow of a fluid through such holes to be precisely determined.

However, machining holes using a laser device fitted with a Q switch providing trains of pulses of very short length, within the nanosecond range, raises problems of efficiency for machining holes. Indeed, machining holes, particularly of a certain
30 depth, requires a large number of such successive pulses, which limits the machining speed for such holes and thus the industrial yield of such machining. Moreover, this type of laser device is relatively inflexible since it does not enables the profile of the pulses generated by the resonator to be varied to obtain pulses with an intensity

profile suited to machining each different type of hole. The machined hole geometry is thus difficult to vary due to the lack of adjustment flexibility of the parameters defining the very short pulses generated by the resonator. Further, holes of a relatively large diameter cannot be machined with pulses in the nanosecond range without using a machining method requiring drilling several holes along a circular outline. Finally, the Q switch frequency is limited because of the formation of a plasma during a short period, the plasma absorbing the luminous energy from a following pulse if it is still present above the hole machining area.

It is an object of the present invention to provide a laser device for drilling holes in fluid injection device components, particularly for fuel, which has good operating stability, a high level of hole machining precision and which allows said holes to be machined at a relatively high speed to obtain a high industrial yield.

It is another object of the invention to provide a device of this type that limits the necessary investment costs while preserving the efficiency thereof.

The invention therefore concerns a laser machining device for drilling holes in fluid injection device components, particularly for injecting a fuel into a combustion engine, the machining device comprising a laser resonator formed of a first solid state active medium and first optical pumping means, said first pumping means being formed by laser diodes. Said resonator is arranged for generating primary pulses in the microsecond range. This laser machining device comprises modulation means arranged downstream of said resonator and providing a train of secondary pulses at output for each primary pulse entering therein.

Owing to the features of the laser machining device according to the invention, it is possible to pierce holes efficiently and with great precision, i.e. with low machining tolerances, in fuel injection device components, for example in an injection nozzle or a throttling orifice used for determining the flow rate of a fluid. This device enables primary pulses of relatively long length to be generated, in particular greater than 50 μ s. It has been observed that a train of pulses each with a relatively short length, for example between 1 and 20 μ s, increases the drilling yield and precision by means of a laser device. However, this efficiency decreases with periodic pulses in the nanosecond range generated by a resonator with a Q switch. In fact, it has been observed within the scope of the present invention that the machining yield for hard materials is lower in the nanosecond range than in the microsecond range. However, the machining precision requires that the energy per pulse must not be increased too much. The device according to the invention generates a second pulse train of this type with an optimum intensity profile owing to the modulation means provided downstream of a laser resonator without a Q switch supplying primary pulses whose

energy is greater than that of a secondary pulse. The laser device is thus arranged to provide, in relatively short periods, a relatively large quantity of energy for quickly machining holes while modulating the luminous intensity to obtain precise and clean drilling. Another advantage of the modulated pulses is the optimisation of the drilling method relative to the dynamics of the plasma generated by the laser pulses. The primary pulses can be periodically supplied for machining a plurality of holes with a high industrial yield.

The modulation means are for example formed by a Pockels cell. Such cells can be controlled precisely and can also cause the secondary pulse train intensity profile to vary at the output of the cell to optimise the hole drilling efficiency depending on the material in which the holes are made and also depending on geometrical parameters defined for the holes.

It will be noted that the combination of a diode pumped laser resonator providing primary pulses in the microsecond range, in particular of the order of tens or hundreds of microseconds, with means for modulating said primary pulses for varying the temporal distribution of energy by forming a plurality of pulses of shorter periods constitutes a particularly efficient solution, since it adds the advantages of resonator yield and stability to flexibility in the generation of energy distribution reaching the machined material and thus the drilling precision. As a result of the features of the invention, that laser machining device thus allows holes to be machined in a reproducible manner with low tolerances. The device according to the invention is thus particularly well suited to drilling holes of throttling orifices in the components of a fluid injection device or system, in particular a fuel injection device.

The laser machining device according to the invention will be described in more detail hereinafter with reference to the annexed drawings, given by way of non-limiting example and in which:

- Figure 1 shows schematically the main elements of a preferred embodiment of the invention;

- Figure 2 shows the various elements of a first embodiment of the resonator of the device of Figure 1;

- Figure 3 shows the transformation of the laser beam by the modulation means of the device of Figure 1;

- Figure 4 shows a second embodiment of the resonator of the device of Figure 1, and

- Figure 5 shows schematically a particular arrangement of the amplification means of the device of Figure 1.

With reference to Figures 1 to 3, a first embodiment of the invention will be described hereinafter. This device comprises a resonator 4 supplying a laser beam 6 having linear polarization. This beam 6 is formed of a succession of primary pulses in the microsecond range. It is provided to modulation means 8 arranged for modulating the incoming laser beam so as to vary the beam intensity distribution, i.e. to vary the power profile thereof so as to form secondary pulse trains of shorter length than the primary pulses supplied by resonator 4. "Pulses in the microsecond range" mean pulses whose length is greater than $1\mu\text{s}$, in particular, between $50\mu\text{s}$ and 1 millisecond.

10 In a preferred variant of the invention, the laser machining device is arranged such that the primary pulses generated by resonator 4 each allow a hole to be made in the machined component. This allows a high industrial yield to be obtained in manufacturing injection device components, without adversely affecting machining precision and the quality of the holes made owing to modulation means 8, in particular
15 formed of a Pockels cell. Moreover, this solution allows a very high energetic yield to be obtained for an active medium formed of an Nd:YAG crystal type diode pumped solid state laser (DPSSL). However, the combination of this type of resonator with modulation means arranged downstream allows secondary pulse trains of shorter length to be obtained, in particular between 1 and $20\mu\text{s}$ as is shown in Figure 3. By
20 way of example, the length of the primary pulses 10 supplied by the resonator is between $50\mu\text{s}$ and 1ms. Pockels cell 8 modulates primary pulse 10 and supplies a secondary pulse train 12 at output, the length of each pulse being comprised between 1 and $20\mu\text{s}$. It should be noted that the Pockels cell can be controlled to precisely define an optimum power profile for the selected application. Thus, power modulation
25 is not necessarily binary, but can vary between a non-zero minimum and given maximum.

Laser beam 16 exiting modulator 8 remains linearly polarized. This beam 16 then enters an optical diode 18 formed, for example, by a linear polarizer and by a quarter-wave plate arranged following the polarizer. Laser beam 20 exiting this optical
30 diode has circular polarization. Beam 20 then enters an amplifier 22 arranged for amplifying the secondary pulse trains 12. Generally, this amplifier is formed by an optically pumped solid state active medium.

Advantageously, it is possible to control the amplification means so as to vary the amplitude of the secondary pulses, at the heart of the same secondary pulse train,
35 by a time lag of the pulse generated in the amplification means with respect to the envelope of the primary pulse entering in this amplification means. The leading or

trailing edge of the amplification pulse is thus used to modulate the amplitude of the secondary pulses.

Optical diode 18 is mainly used to protect resonator 4 from reflections from amplifier 22 and also from machining head 24 following the amplifier. Laser beam 26 exiting amplifier 22 is still circularly polarized, as is beam 28 exiting machining head 24.

The machining head comprises focussing means and can also comprise a beam expander preceding the focussing means.

It will be noted that the arrangement of an optical diode in the device of Figure 1 increases the efficiency of the device and in particular increases the quality of the laser beam supplied. Moreover, this optical diode ensures that the resonator is stable by preventing disturbance and/or interference in the resonant cavity. This thus ensures good reproducibility from one primary pulse to another and thus good reproducibility of the pulse trains supplied by the device at the exit of machining head 24.

Resonator 4 is shown in more detail in Figure 2. It comprises in a conventional manner a positioning laser 32 for adjusting the position of the resonant cavity elements and also for correctly orienting the part to be machined relative to the laser beam. Next, it comprises in a conventional manner a mirror 34 and a partially reflective mirror 36. It also comprises a beam separator 38 for measuring the energy of the beam using measuring means 40. It further comprises a safety shut-off device 42 and finally an expander 44 for increasing the diameter of the laser beam generated. In the embodiment of Figure 2, resonator 4 further comprises a linear polarize 46 and a diaphragm 48. The resonator comprises a cavity 52 formed of an Nd:YAG crystal solid state active medium. In the case of the present invention, this active medium is optically pumped by laser diodes arranged in a manner known to those skilled in the art, particularly in the form of a diode bar or matrix.

As mentioned previously, the laser machining device according to the present invention allows a high quality beam to be obtained, suitable for the precise machining of holes in various components, particularly fluid injection device components. This means particularly a beam which is circular, which has substantially constant intensity distribution and which can be precisely focussed with a relatively small focal point diameter. The device also exhibits very good stability. This stability is characterized by low mean power fluctuation, by low resonator-generated primary pulse power variation and finally by low power variation of the secondary pulse train supplied by the laser device, and low secondary pulse train intensity distribution.

The device of the invention generates laser pulses with an energy variation of less than 1%. This means a low machining tolerance relative to the surface of the apertures defined by the holes and thus a low fluid flow variation through the latter.

Microsecond range pulses generated by the resonator are generated for
5 example with a frequency varying between 1Hz and 1kHz. The length of each of such pulses varies for example between 10 microseconds (μ s) and several milliseconds (ms) whereas the length of the secondary pulses at the modulator output can vary between 1 and 50 μ s. Using suitable amplification means which will be described more particularly hereinafter, the supplied pulse peaking capacity can be comprised for
10 example between 100W and 100kW. The diameter of the laser beam before the focussing optic is typically less than 50 mm. Given the quality of the laser beam obtained, it is possible to focus it precisely and to adjust the distance of the focal point relative to the components to be machined in a very precise manner, in particular with a tolerance less than 50 μ m. It will be noted that precise adjustment of
15 this distance also enables the profile of the machined hole to be defined in accordance with its longitudinal section.

The device according to the invention enables holes with a diameter comprised between 5 μ m and 1mm to be machined. Machining precision is relatively high, i.e. identical holes can be successively machined in a reproducible manner and with low
20 tolerances. A conicity tolerance of less than 5% of the diameter of the hole is obtained. Deformation of the circular profile of the hole is less than 5% of the diameter. The reproducibility of one predefined hole to another can be considerably less than 5%, particularly less than 2%. These very good tolerances result in particular from the use of a resonator formed of a diode pumped solid state laser active medium
25 arranged to provide primary pulses of relatively long length, which are then modulated by modulation means, in particular a Pockels cell, to supply secondary pulse trains whose intensity distribution can be adapted in an optimum manner depending on the drilling dynamics and in particular on the material in which the hole is made, as well as the dimensions of said hole.

30 Figure 4 shows a second embodiment of the resonator arranged in the laser machining device of the invention. Those elements that have already been mentioned will not be described again here in detail. Resonator 50 differs essentially from that of Figure 2 in that the oscillator 56 is formed by a ND:YVO₄ crystal. This crystal has the peculiarity of directly supplying a linearly polarized laser beam such that integration of
35 a polarizer in resonator 50 is superfluous. For a certain optical pumping power, this provides a laser beam with a much greater intensity than that supplied by the resonator of Figure 2, given that the integration of polarizer 46 substantially reduces

the luminous intensity provided by half. The use of such a crystal is known for resonators with a Q switch supplying pulses with a very short length, but it has not been proposed by those skilled in the art in a resonator arranged for supplying relatively long pulses, without integration of a Q switch. The use of such a crystal is
5 actually particularly suited to the device of the invention given that the modulation means described hereinbefore generally require linear polarization for the incoming laser beam. It will be noted that those skilled in the art know other crystals having the same property.

As regards polarization, it will also be noted that the arrangement of the
10 various elements provided in the device shown in Figure 1 allow a circularly polarized laser beam to be obtained at the exit of the machining head, which is particularly suitable for machining holes.

According to a particular embodiment of the invention, amplification means 22 described hereinbefore are formed of at least two solid state active mediums as
15 shown schematically in Figure 5. In Figure 5 laser pulse amplification means 60 are formed of two cavities 62 and 64 each comprising a solid state medium 66, respectively 68, optically pumped by flash lamps 70.

The use of flash lamps in the amplification means constitutes a particular embodiment of the present invention, also in the case where amplification means 22
20 comprise a single cavity. The main reason for arranging a flash lamp in the amplification means is currently economical. In fact the use of laser diode matrices remains relatively expensive. In the case of the present invention, it was observed that the use of flash lamps in the amplification means had a relatively innocuous influence on the laser beam quality and on the stability of the laser machining device. In fact the
25 use of flash lamps in the amplification means is much less critical than for the resonator in which the laser beams are generated.

Finally, it will be noted that those skilled in the art can provide various arrangements for the amplification means for obtaining several amplification levels for the laser beam. Associated with other optical elements, it is possible to envisage embodiments in which the laser beam passes at least twice in each cavity. Moreover, it is to be noted that within the scope of the present invention as claimed, the optical state of the amplifier can also be pumped by laser diodes.